LIGHTWEIGHT, LIGHT-TRAPPED, THIN GaAs SOLAR CELL FOR SPACECRAFT APPLICATIONS: PROGRESS AND RESULTS UPDATE[1]

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ABSTRACT

Progress is reported with respect to the development of ultra-lightweight, high performance, thin, light trapped GaAs solar cells for advanced space power systems. Conversion efficiencies of 17.9% (AM0, 1X) have been demonstrated for a 3 μm thick, 1 cm^2 solar cell. This results in a specific power of over 1020 W/kg (with a 3 mil cover glass) and a power density of 240 W/m^2. Device parameters were 1.015 volts open circuit voltage, 80% fill factor, and a short-circuit current density of 29.54 mA/cm^2. In addition to silicone bonding, the use of electrostatic bonding to attach the cover glass support to the front surface enables an ultra-thin, all back contact design that survives processing temperatures greater than 750°C. This also results in a 10% reduction of the cell weight for a potential specific power of 1270 W/kg. All back contact, ultra-thin, electrostatically bonded GaAs sola cell prototypes have been fabricated demonstrating an open circuit voltage of 1 volt for a cell base thickness of 1 μm with a 0.5 μm emitter. This technology will result in a revolutionary improvement in survivability, performance, and manufacturability of lightweight GaAs solar cell products for future Earth-orbiting science and space exploration missions. The thin, electrostatically bonded, all back contact GaAs device technology has multiple uses for specialty high performance solar cells and other optoelectronic devices.

INTRODUCTION

A schematic cross-sectional representation of the silicone bonded AstroPower prototype thin GaAs solar cell design is shown in Figure 1. This device is supported by a 3-mil cover glass which has been attached to the front surface with a 1-mil silicone adhesive.

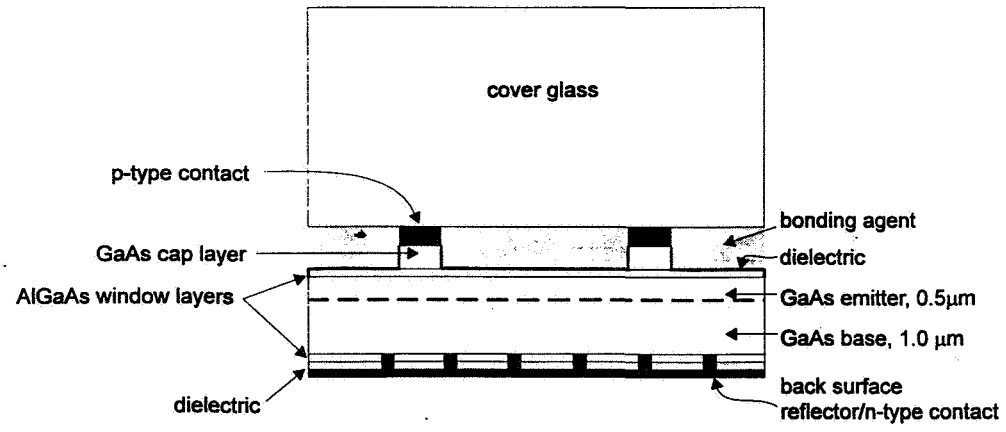

Figure 1. Ultra-thin GaAs solar cell with light trapping.

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The improved device design utilizes electrostatic bonding to attach the cover glass support to the front surface, enabling an ultra-thin, all back contact design that eliminates grid shading. The electrostatically bonded, ultra-thin structure survives process temperatures exceeding 750°C. The conceptual design of this unique solar cell is shown in Figure 2. The p-type region is diffused from the back of the device to the emitter.

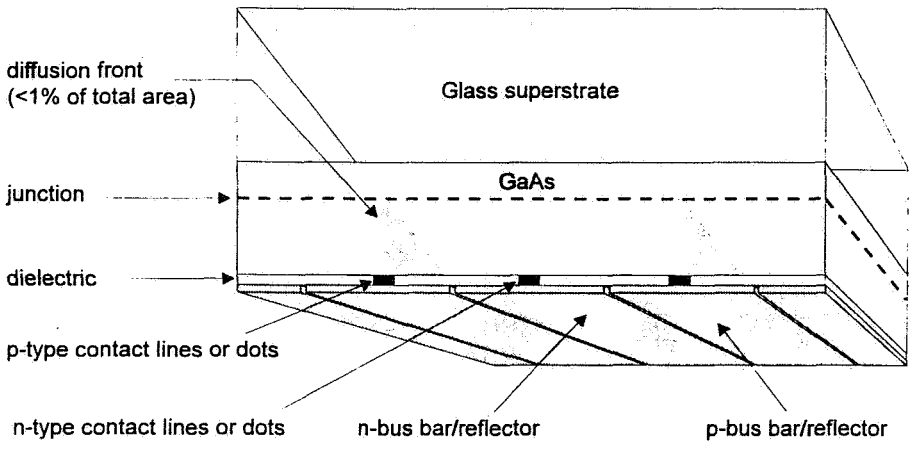


Figure 2. Electrostatically bonded, all back contact, ultra-thin GaAs solar cell.

The benefits of this device technology include the following:

- specific power improvements over state of the art GaAs/Ge devices
- high radiation resistance and lower on-orbit operating temperature
- all back contact design which simplifies electrostatic bonding and eliminates grid shading
- array tabbing does not require wraparound interconnections
- enables cost-effective manufacturing, eliminates adhesive degradation, and provides high structural integrity
- transferable to any epitaxial growth technology and various solar cell materials and designs including tandem solar cells and high voltage concentrator cells
- applicable to integrated logic components, LEDs, LED displays, flat screen display drivers, waveguides, and microwave devices

High Performance Benefits

The ultra-thin, lightweight, light-trapped GaAs solar cell design offers a high specific power in comparison to silicon and GaAs/Ge devices, which is important for space applications (ref. 1). Light trapping increases the effective optical path length with the use of a reflector. The benefits of light trapping in GaAs can be realized by increased optical absorption, collection efficiency and photon recycling (ref. 2). These features lead to increased open circuit voltages and short circuit currents (ref. 3).

Radiation damage is the primary degradation mechanism for GaAs solar cells deployed in space. The ultra-thin, light-trapped GaAs solar cell will have significantly increased EOL efficiencies compared with conventional solar cell structures because of the thin device layers associated with the structure. This design will be less sensitive to changes in bulk diffusion length due to the increased optical path length and decreased recombination volume.

Thermal stability and tolerance to UV degradation are inherent to the thin device structure and electrostatically bonded 3-mil glass superstrate. There is neither a darkening effect such as that which occurs with adhesives after extended exposure to UV light, nor degradation of the bond interface. The maximum power to

weight ratios can be attained since no additional material is used to form the bond and the electrostatic bond will not suffer from degradation upon exposure to high temperatures.

The all back contact technology enables tabbing to the p-type and n-type regions of the device to be easily accomplished from the back of the structure. Placement of the grid pattern for both the n- and p-type contacts on the back of the solar cell eliminates grid shading losses for light entering the front of the device. In contrast to other coplanar contact designs, this technology eliminates the need for micro-machining the solar cell.

The high performance benefits of AstroPower's ultra-lightweight, thin, light trapped GaAs solar cells enable the devices to meet the technology demands for solar cells with increased performance, as required for the space cell industry (ref. 4).

RESULTS AND DISCUSSION

The highest efficiency obtained for an ultra-thin, adhesive bonded, LPE grown device achieved to date at AstroPower is 17.9%. The results of the current-voltage and quantum efficiency measurements are shown in Figures 3 and 4. As can be seen, the open circuit voltage and fill factor are quite high. The quantum efficiency measurement indicates some losses in blue response which can be improved with optimization of the emitter and window layer.

Table I lists the weight contribution of the major material components for this solar cell. Reducing the device thickness to 2 microns, with a 2 micron-thick GaAs contact layer, would reduce the GaAs contribution to 5% of the total cell weight. Also, with the electrostatically bonded, all back contact device, the weight of the adhesive, which is approximately 10% of the total cell weight, would be eliminated. This weight reduction will lead to the highest possible power densities (greater than 1270 W/kg) for these ultra-thin solar cells.

Voc	1.015V
Jsc	29.54 mA/cm^2
Fill Factor	80.3%
Area	1 cm^2
Thickness	3 μm
Specific Power	1020 W/kg
AM0, 1X efficiency	17.9%

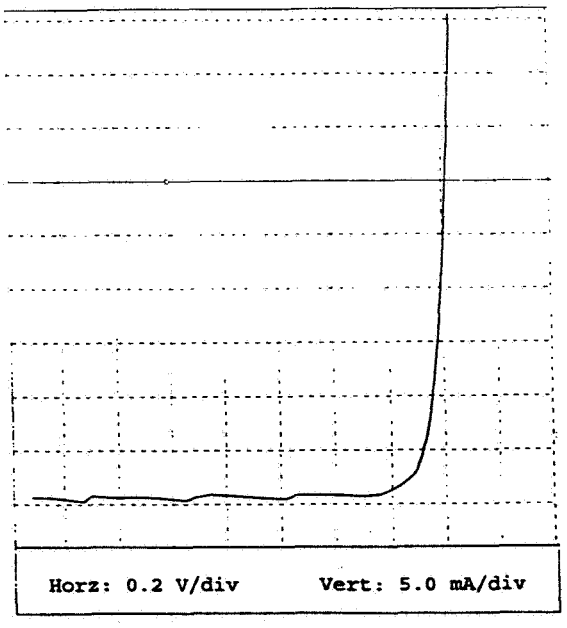


Figure 3. Current voltage measurement for ultra-thin device G13901A.

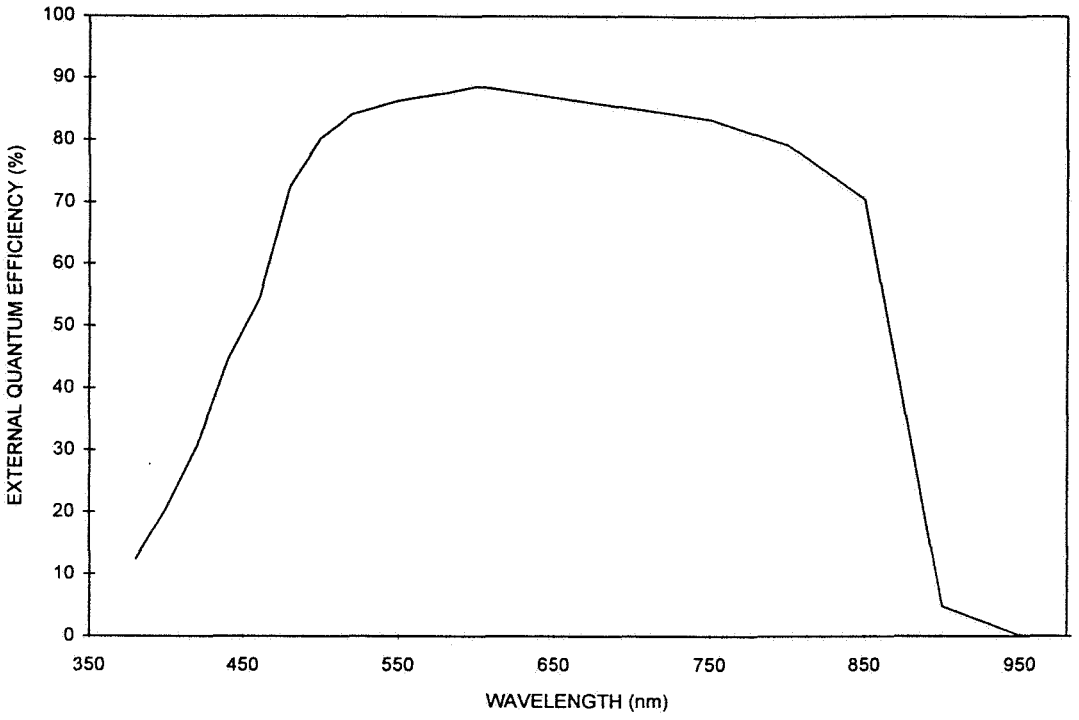


Figure 4. *External quantum efficiency measurement for ultra-thin device G13901A.*

Table I. *Weight contribution of the major solar cell components for the ultra-thin device (G13901A).*

Material	Density	Total Weight/cm^2	Percentage of Total Cell Weight
Pilkington CMG glass (3-mil)	2.554g/cm^3	19.46mg	82%
Sylgard Silicone Adhesive (1-mil)	0.9g/cm^3	2.29mg	10%
Gallium Arsenide	5.32g/cm^3	1.85mg	8%

Typical values for the dark diode reverse saturation current densities for the GaAs solar cells are $3x10^{-19}$A/cm^2 and $5x10^{-11}$A/cm^2 for the diffusion and depletion region recombination components respectively. These current densities provide an indication of the junction quality, minority carrier lifetime, and surface passivation for the device. The dark diode current values obtained at AstroPower are among the best reported by a number of researchers for high efficiency GaAs solar cells (refs. 5, 6, and 7), further demonstrating the value of near equilibrium growth processes.

Light-trapping has been demonstrated on the ultra-thin devices. The external quantum efficiency curve illustrated in Figure 5 shows an increase in long wavelength response (between 650 and 870 nm) of the thinned solar cell with a back surface reflector, compared to the same device before the thinning procedure (on the GaAs substrate). The external quantum efficiency of this device was increased by 5.2% at 850 nm with the incorporation of a back surface reflector. The gain in short circuit current density for this solar cell is approximately 0.7 mA/cm^2. This gain is expected to increase as the active device thickness is decreased to less than 2 microns. The blue response of this device was low due to a non-optimized AlGaAs front surface passivation layer.

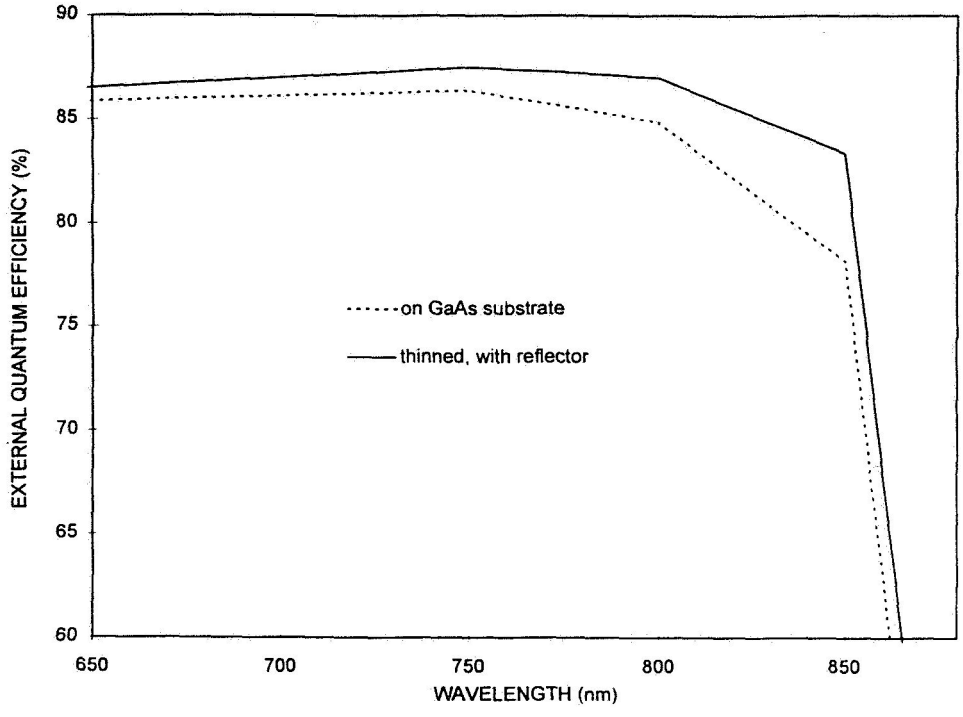
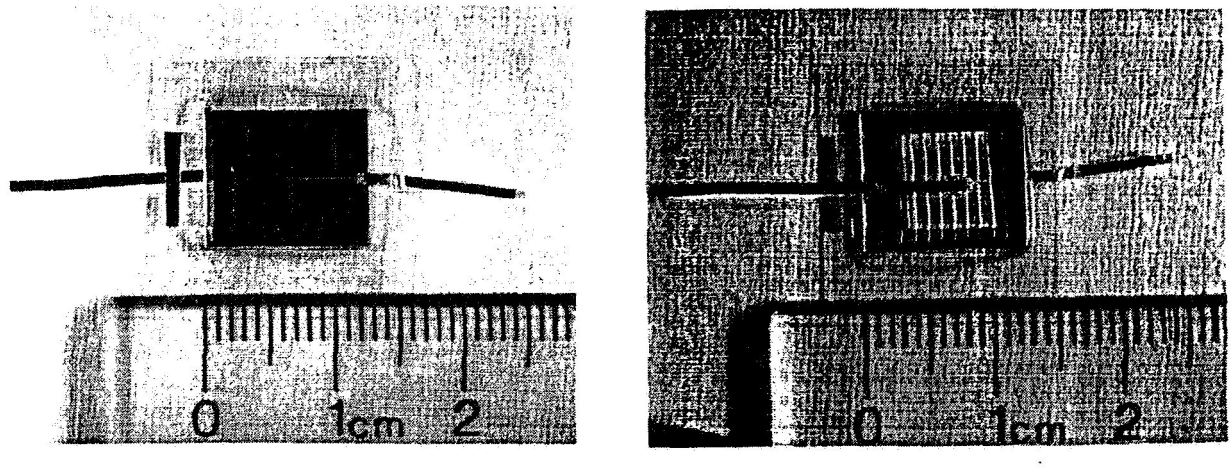


Figure 5. External quantum efficiency of sample G13405B.

Photographs of the ultra-thin, light trapped device are shown in Figure 6. The front surface is shown in Figure 6a and the back surface including the n-type contacts and silver reflector is shown in Figure 6b.



(a) (b)

Figure 6. Photograph of the front (a) and back (b) surface of the ultra-thin, light trapped GaAs solar cell.

Fabrication of large area (8 cm^2) devices is underway. A photograph of an 8 cm^2 GaAs solar cell fabricated on the GaAs substrate is shown in Figure 7. Similar devices are being processed as ultra-thin, light trapped solar cells. The results of six 1 cm^2 devices processed from one 2x4 cm^2 LPE growth are shown in Table II. The performance of these devices demonstrates the capability of the material to support large area devices.

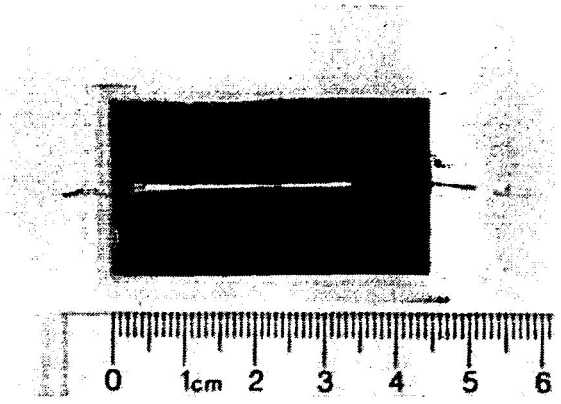


Figure 7. *Photograph of a large area (8cm^2) GaAs solar cell.*

Table II. *Current-voltage characteristics of six 1 cm^2 devices fabricated from one large area (8cm^2) LPE growth.*

Cell Number	Voc (V)	Jsc (mA/cm^2)	Fill Factor (%)	Efficiency (AM0, 1X, 25°C) on GaAs substrate (%)	Efficiency (AM0, 1X, 25°C) of Ultra-thin Device (%)
G13901A	1.020	29.0	78.9	17.29	17.98
G13901B	1.015	30.0	79.3	17.89	17.56
G13901C	1.007	29.1	78.3	16.98	16.98
G13901D	1.008	30.2	73.8	16.64	13.94
G13901E	1.011	31.0	78.4	18.20	17.30
G13901F	0.987	30.8	72.5	16.33	15.17
Median	1.010	30.1	76.4	17.14	17.14

For the all back contact, electrostatically bonded, ultra-thin GaAs solar cells, the p-type emitter is extended to the back of the solar cell by a selective diffusion. The surface area of the diffusion front is less than 1% of the total area of the ultra-thin solar cell. Zinc diffusion profiles were determined by electrochemical CV profiles at BioRad Semiconductor in Mountain View, California. The electrochemical CV profiles for two zinc diffusions into n-type GaAs substrates (Si: 0.89-3.92x10^{18}/cm^3) are shown in Figures 8. Figure 8a shows the results of a 2 hour zinc diffuison at 700°C. The p-region extends at least 1.5 microns into the GaAs substrate and has a high conductivity. The results of a 2 hour zinc diffusion at 750°C are shown in Figure 8b. the p-region extends at least 3 microns into the GaAs substrate and has a high conductivity (50(Ω-cm)$^{-1}$). These measurements indicate that the resistance of the zinc diffused regions is minimal and the width of the back contact fingers can be reduced to less than 25 microns without hindering the performance of the solar cell.

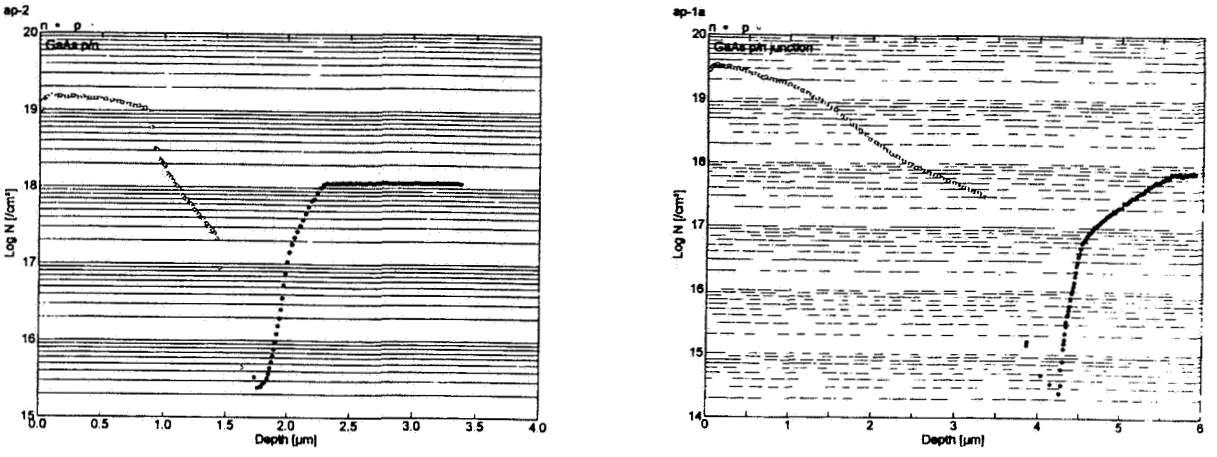


Figure 8. Electrochemical CV profiles for zinc diffusion into a GaAs substrate a) 2 hour zinc diffusion at 700°C and b) 2 hour zinc diffusion at 750°C.

In order to achieve a high efficiency, ultra-thin, all back contact solar cell, a high temperature glass formulation that is CTE matched to GaAs and has a high softening point has been developed. This glass has a softening point of 890°C, and a CTE of 6.0×10^{-6}/K. The annealing point of this glass is approximately 650°C. Void-free, 6 cm^2 bonds to LPE GaAs layers on GaAs substrates have been obtained with this high temperature glass.

GaAs solar cell structures electrostatically bonded to this glass survive the substrate removal procedure and subsequent processing steps. Ultra-thin (less than 5 microns) GaAs/glass laminates have been heat cycled to 750°C for two hours and cooled in liquid nitrogen with no degradation of the bond interface. Electrostatic bonding to this high temperature glass formulation enables high temperature device processing to occur after coverslide bonding. Future plans include space qualifying this glass with the appropriate testing laboratory and continuing to work with the glass manufacturer to ensure space survivability of the glass superstrate.

Prototype all back contact devices are presently being processed. To date, open circuit voltages of 1 volt have been demonstrated for a cell base thickness of 1.0 micron with a 0.5 micron emitter. In addition to completing 16 and 25 cm^2 all back contact solar cells on LPE material, this technology will be demonstrated on MOCVD material over the next few months.

CONCLUSIONS

High performance, lightweight, thin, light trapped GaAs solar cells have been demonstrated. Conversion efficiencies of over 17.9% (AM0, 1X) have been demonstrated resulting in a specific power of 1020 W/kg (with a 3-mil cover glass) and a power density of 240 W/m^2. The incorporation of light trapping has increased the external quantum efficiency of these solar cells in the long wavelength range. Large area, electrostatically bonded, ultra-thin GaAs solar cell structures have demonstrated survivability to 750°C, with no degradation of the bond interface. Prototype all back contact devices with open circuit voltages of 1 volt have been fabricated. Future plans include completing 4 cm^2 all back contact, electrostatically bonded, thin, light trapped GaAs solar cells on both LPE and MOCVD material for a potential specific power of 1270 W/kg.

The success of this program can lead to the deployment of high performance, thin GaAs solar cells in the space environment. AstroPower's solar cell design can have a significant impact on the longevity and power generation capabilities of space power supplies. The fabrication technology has multiple uses for specialty high performance solar cells and other optoelectronic devices.

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